JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 106, NO. E12, PAGES 33,021–33,024, DECEMBER 25, 2001

Upper bound on Io's heat flow

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Abstract. Analysis of the temperatures and areas of Io's thermal anomalies yields an upper bound on the total heat flow. An extended distribution function allows an assessment of the heat flow from undetected, cooler (but larger) anomalies and predicts a limiting temperature of ~90–95 K for the surface. This value is in agreement with measured Voyager infrared interferometer spectrometer and Galileo Photo-Polarimeter Radiometer nighttime "minimum temperatures." In addition, the lack of dependence on both latitude and time of night for these observed temperatures can be explained by cooling lavas on a global scale. We consider the extreme case that Io may be covered completely by lava in various stages of cooling to the exclusion of any thermally passive 'background' (excepting the few high mountains). Such a distribution of volcanic thermal anomalies up to the size of Io itself yields the first upper bound for heat flow, 13.5 W m^{-2}. This corresponds to a total global, radiated power of 5.6×10^{14} W.

1. Introduction

Io's heat flow is thought to be a product of tidal dissipation in its interior. This heat flow is important because it provides strong constraints on interior models, on the dissipation within Jupiter, and on the evolution of the orbits of the Galilean satellites [*Peale et al.*, 1979; *Yoder and Peale*, 1981]. Thermal radiation from Io's volcanically active surface regions can be detected with infrared (and at times even visual) detectors. Io has small anomalies at very high temperatures and larger anomalies at cooler temperatures. A lower limit on the total heat flow is calculated by summing the radiated power from the warmer thermal anomalies that are derived from observations at wavelengths ≤ 20 μm.

With the successes of ground-based observation campaigns and of the Galileo mission, additional information has become available which allows us to derive the first upper bound for Io's heat flow. Even the lower bounds on Io's heat flow are difficult to reconcile with current models of power available from tidal dissipation models [*Greenberg*, 1989]. Higher values of heat flow in this range may require nonequilibrium tidal dissipation. The upper bound on heat flow implies a Q of 3–6 which may be unrealistically low and suggests very heterogeneous dissipation within Io.

2. Molten Lava and Io's Heat Flow

A number of possible compositions have been suggested for Io's lavas. However, the discovery of erupting, high-temperature lava excludes sulfur for the primary lava [*Johnson et al.*, 1988; *Veeder et al.*, 1994; *Blaney et al.*, 1995; *Davies et al.*, 1997; *Stansberry et al.*, 1997; *McEwen et al.*, 1998]. Now there are data for eruption temperatures in the 1600–2000 K range which suggest ultramafic compositions for at least some of Io's lava (e.g., komatiite [*Matson et al.*, 1998; *McEwen et al.*, 1998; *Davies et al.*, this issue].

Ground-based, telescopic-monitoring programs have found that large, hot eruptions are observable from the Earth ~6% of the time [*Sinton et al.*, 1983; *Veeder et al.*, 1994]. The Galileo mission has also captured observations of many eruptions of high-temperature silicate lava [e.g., *McEwen et al.*, 1998]. Flow modeling has led to estimates of effusion rates as large as ~$3–8 \times 10^5$ m^3 s^{-1} for individual eruptions [*Blaney et al.*, 1995; *Davies*, 1996]. The corresponding resurfacing rate by lava for all of Io is more than ~1.3 cm yr^{-1}. These rates are consistent with a lack of craters [*Johnson and Soderblom*, 1982] and the observed size and temperature distributions of infrared "outbursts" [*Veeder et al.*, 1994; *Blaney et al.*, 1995; *Davies*, 1996]. Thus the chief mechanism for Io's heat flow is relatively simple. Heat from Io's interior is brought to the surface by eruptions of very hot silicate lava. When eruptive episodes subside, vast areas of solidified, cooling lava are left on the surface. The bulk of the heat is conducted a relatively short distance to the surface of the flow where it is radiated to space as thermal emission. Conductive transport of heat through the crust from the deep interior becomes insignificant [cf. *Gaskell et al.*, 1988].

Sulfur, SO_2, and other volatiles are active at the surface and are needed to satisfy spectral reflectance and other data. Possible sulfur lavas are of secondary importance because they do not contribute significantly to either the heat flow or the size-temperature distribution of thermal anomalies [*Veeder et al.*, 1994; *Blaney et al.*, 1995; *Matson and Blaney*, 1999].

3. Heat Flow Values

Published heat flow determinations are plotted in Figure 1. The first four values and the sixth value are derived from telescope data [*Matson et al.*, 1980, 1981; *Sinton*, 1981; *Morrison and Telesco*, 1980; *Johnson et al.*, 1984; *Veeder et al.*, 1994]. The fifth and seventh values are derived from Voyager infrared interferometer spectrometer (IRIS) data *McEwen et al.* [1992, 1996]. The eighth and ninth values are derived from Galileo Photo-Polarimeter Radiometer (PPR) data [*Spencer et al.*, 2000a, 2000b]. These approaches identify thermal anomalies and then sum their radiated power to obtain lower limits on the "observed heat flow" (with appropriate bias corrections).

Overall, the results are remarkably consistent with each oth-

Paper number 2000JE001374.
0148-0227/01/2000JE001374$09.00

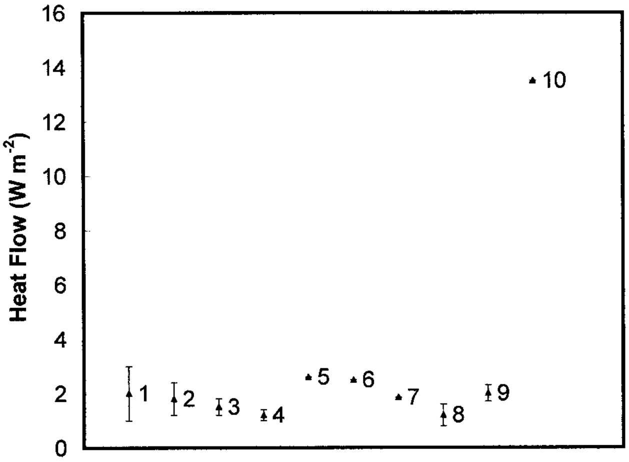

Figure 1. Bounds on Io's heat flow. Points labeled 1–9 are lower bounds. The tenth point is our new upper bound. Sources are (1) *Matson et al.* [1980, 1981], (2) *Sinton* [1981], (3) *Morrison and Telesco* [1980], (4) *Johnson et al.* [1984], (5) *McEwen et al.* [1992] (Voyager IRIS data), (6) *Veeder et al.* [1994] (ground-based IRTF multiband-pass radiometry), (7) *McEwen et al.* [1996] (Voyager IRIS), (8) *Spencer et al.* [2000a] (Galileo PPR data), (9) *Spencer et al.* [2000b] (Galileo PPR data), and (10) this paper.

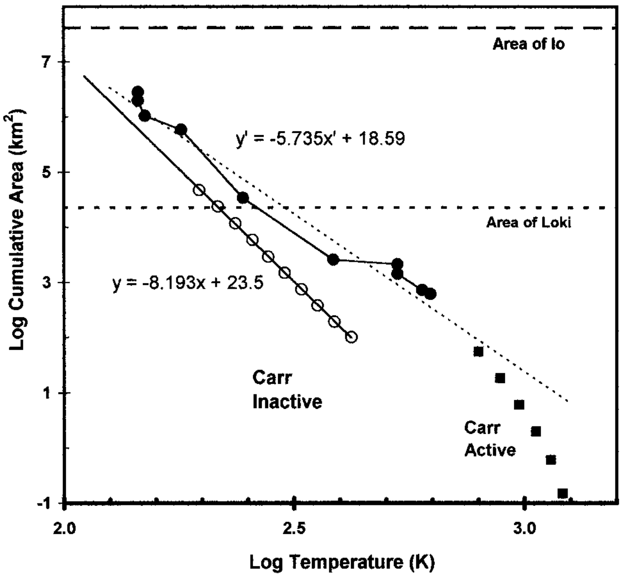

Figure 2. A log (cumulative area) versus log (temperature) plot for the model thermal anomalies of 1983 [*Veeder et al.*, 1994]. The area of Loki and the total surface area of Io (km^2) are indicated by horizontal dashed lines. "Active" and "inactive" models from *Carr* [1986] are compared.

er; especially since they were derived by several different techniques, from different assumptions, or both. A common characteristic of 1–9 is that they remain lower bounds for the total heat flow. Thermal anomalies produced by initially hot lava will gradually cool with time. As they approach equilibrium with absorbed insolation they become more difficult to detect with current techniques. For instance, the falloff of instrumental sensitivities with wavelength results in cutoff temperatures below which anomalies can no longer be detected. Investigators have recognized that there must therefore be some cooler anomalies. These are expected to contribute significantly to the heat flow due to their large sizes but have not been included in heat flow summations. Furthermore, for the ground-based telescopic determinations, high-latitude sources are underestimated due to geometric foreshortening.

4. Upper Bound on Io's Heat Flow

The distribution of temperature with area of the thermal anomalies can be used to set an upper bound on Io's heat flow. We use the thermal anomalies reported by *Veeder et al.* [1994]. This is the largest and the most uniform set available. Variations of the anomalies on time scales of less than a decade are represented in this sample. Consider a plot of log (cumulative area) versus log (temperature), as shown in Figure 2 for the 1983 anomalies. The ordinate for a point in Figure 2 represents the total area that is either at that temperature or at a higher temperature. Model calculations of eruptions and cooling lava show similar functional relationships between temperature and area as seen in Figure 2 [cf. *Carr*, 1986; *Davies*, 1996; *Howell*, 1997]. As an illustration, the results of two of Carr's models are plotted for comparison with global thermal anomalies. Carr originally considered the IRIS spectra for Loki [*Hanel et al.*, 1979].

The anomalies for all of the apparitions are plotted in Figure 3 (connecting lines are omitted for clarity). Note that the intrinsic temperature of an anomaly as defined by *Veeder et al.* [1994] is the surface temperature that heat flow maintains in the absence of other sources of power. There are no points below a temperature of 135 K. This cutoff is due to instrumental sensitivity and other limitations of the observations and

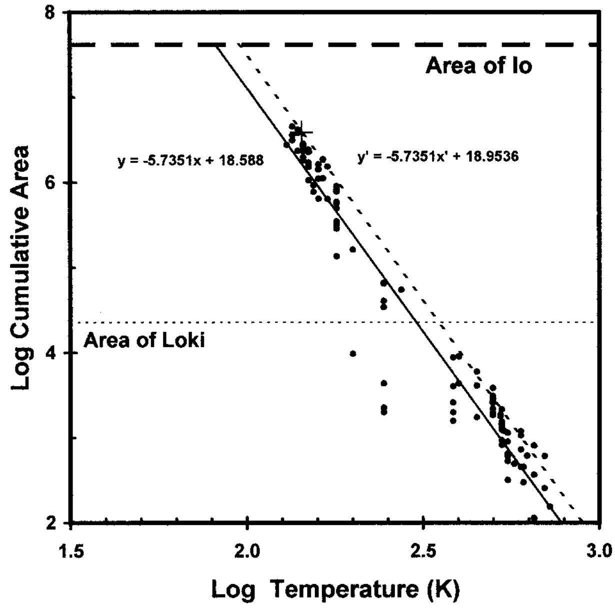

Figure 3. A log (cumulative area) versus log (temperature) plot for all model thermal anomalies for 1983 to 1996 [*Veeder et al.*, 1994; *Blaney et al.*, 1995]. The area of Loki and the total surface area of Io (km^2) are indicated by horizontal dashed lines. The solid curve is a least squares fit to all the points. The parallel, dashed curve that lies above it is indicative of an upper envelope. The lower curve intersects the area of Io at 82 K, while the upper curve intersects at 95 K.

modeling technique. Since lava continues to cool, there must be a significant population of undetected thermal anomalies below that temperature. Next, we discuss a bound on this population. Two reference distributions were constructed. The solid curve is a least squares fit to the log values of the plotted points. The parallel, dashed curve that lies above it is indicative of an upper envelope for the plotted points. The horizontal dashed line near the top of the frame represents the surface area of Io. The lower curve intersects the area of Io at 82 K, while the upper curve intersects at 95 K. These temperatures are also supported by the particular case of *Carr*'s [1986] Loki model for an inactive flow which extrapolates to an intersect temperature of 87 K (Figure 2).

Io's surface area is reached with extrapolations by factors of ~1.5 in temperature and ~10 in area. In terms of heat flow it implies about a sixfold increase over previous summations, which were limited to higher temperature sources.

These straightforward extrapolations assume implicitly that the physical processes involved apply throughout the indicated size and temperature ranges and thus the trends continue monotonically. There are several effects which might result in the actual distribution falling below these extrapolations. Phase changes in cooling lava are possible. However, none are expected in silicate lava between 82 K and 135 K. Condensation of SO_2 frost or other material on the surface may momentarily impede the heat flow due to lower conductivity. However, a compensating thermal gradient will quickly build up to continue cooling. Thus, on timescales relevant to heat flow, there is no net change in the outward flow of power from the subjacent lava.

Most of the surface of Io is relatively uniform in the sense that volcanic features appear virtually everywhere [e.g., *Lopes-Gautier et al*., 1999]. However, there may be areas that cannot be covered by lava. High mountains are an obvious example. Such terrain occupies a small percent of Io's surface and is negligible for the present discussion.

Ponding of lava in large calderas and other topographic low regions is also plausible and could result in different impediments to flowing lava. Loki, at a diameter of 170 km, is the largest feature of this type. The area of Loki, represented in Figure 3 as a dashed horizontal line, falls in the midrange of the available data. No significant break due to ponding or other effects is apparent for areas more than an order of magnitude larger or more than 2 orders of magnitude smaller than Loki.

The intersect temperatures of 82 and 95 K can be interpreted as estimates for the limiting temperatures below which surface lavas do not cool (i.e., due to resurfacing). These predictions agree well with Voyager and Galileo temperature data. *McEwen et al*. [1996, p. 844] note that "... nighttime spectra ... show a nearly constant T of 90 ± 5 K." for the coolest component within IRIS fields of view. A. S. McEwen (private communication, 2001) has found a few small areas as low as 63 K. *Spencer et al*. [2000a] agree. The brightness temperature map (their Figure 4) shows that most of these areas lie between the 90 and 95 K contours.

Spencer et al. [2000a] note that these coldest regions have no obvious temperature dependence with latitude. If these temperatures were the result of the release of absorbed insolation, both latitudinal and time-of-night dependencies would be evident. On the other hand, the lack of such dependencies is entirely consistent with temperatures maintained by cooling lava. Another proposed explanation is an ad hoc variation of thermal inertia with latitude (J. R. Spencer, private communication, 2001).

We obtain the upper bound on Io's total heat flow by converting the upper envelope curve in Figure 3 to power via area times $\varepsilon\sigma T^4$, where ε is radiometric emissivity ($\varepsilon \equiv 0.9$) and σ is the Stephan-Boltzmann constant. The result is 13.5 W m^{-2}, which corresponds to a total global radiation of 5.6×10^{14} W, which is plotted as the tenth value in Figure 1. This result is an upper bound on the actual heat flow because we extrapolated from the upper envelope of the thermal anomaly data and because we probably overestimate the contributions of some areas (e.g., mountains). Generating heat flow values close to the upper bound may challenge realistic models for dissipation of tidal energy within Io. For example, high-dissipation, thin shell models discussed by *Cassen et al*. [1982] would require 3–6 for values of Q. In addition, the possibility of large areas of cooling lava may require revisiting the models of daytime temperatures and eclipse behavior [cf. *Sinton*, 1981, 1982; *Pearl and Sinton*, 1982; *Sinton and Kaminski*, 1988; *Veeder et al*., 1994; *McEwen et al*., 1992, 1996; *Matson et al*., 2001].

5. Summary

We set the first upper bound of Io's heat flow of 13.5 W m^{-2}, i.e., a global radiated power of 5.6×10^{14} W. This is ~6 times the average of previous lower bounds (~2 W m^{-2}). Io's heat flow must lie between these upper and lower bounds. Our analysis considers an alternate view for the geothermal state of Io's surface which may be covered almost entirely by cooling lava with even the poles rapidly resurfaced by lava flows. Mountains are the only identified "passive" geologic units whose temperatures may be totally controlled by solar insolation via latitude, hour angle, and their intrinsic thermophysical parameters.

Acknowledgments. This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA. A. G. D. was supported in part by a grant from the NASA Jovian System Data Analysis Program. Comments by an anonymous reviewer were quite helpful.

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(Received September 5, 2000; revised March 28, 2001; accepted April 13, 2001.)